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(71) Applicant: LUCENT TECHNOLOGIES INC.
Murray Hill, New Jersey 07974-0636 (US)

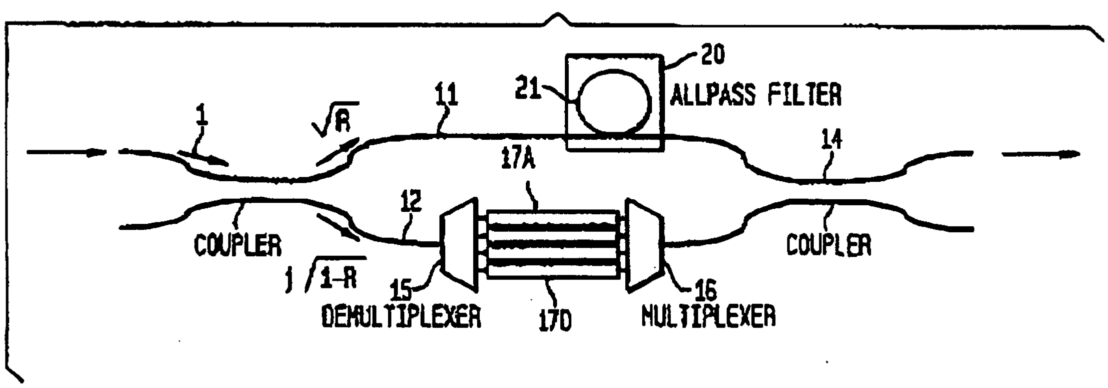
(72) Inventor: Madsen, Christi Kay
South Plainfield, New Jersey 07080 (US)

(74) Representative:
Watts, Christopher Malcolm Kelway, Dr. et al
Lucent Technologies NS UK Limited,
5 Mornington Road
Woodford Green Essex, IG8 0TU (GB)

(54) **Reconfigurable multi-channel filters having enhanced channel bandwidth**

(57) In accordance with the invention, an MZI-based reconfigurable multi-channel filter is provided with enhanced channel bandwidth by adding an all-pass filter to one or both of the MZI arms. The result is a square-shaped amplitude response closely approximating the ideal.

FIG. 2



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Description

FIELD OF THE INVENTION

[0001] This invention relates to optical communication systems and, in particular, to reconfigurable multichannel filters for adjusting the amplitudes of different wavelength channels.

BACKGROUND OF THE INVENTION

[0002] Optical fiber communication systems are beginning to achieve great potential for the rapid transmission of vast amounts of information. In essence, an optical fiber system comprises a light source, a modulator for impressing information on the light, an optical fiber transmission line for carrying the optical signals and a receiver for detecting the signals and demodulating the information they carry. Increasingly the optical signals are wavelength division multiplexed signals (WDM signals) comprising a plurality of distinct wavelength signal channels.

[0003] Reconfigurable multi-channel filters are important components of optical communication systems. Conditions in an optical communication system can change as channels are amplified, added, dropped and rerouted among branches. Multichannel filters are useful in selectively adding or dropping channels and in compensating amplitude variation among different channels. Reconfigurability is needed to adapt to changing conditions.

[0004] One conventional multi-channel filter is based on the well-known Mach-Zehnder Interferometer (MZI). An MZI comprises a pair of waveguiding arms extending between a pair of couplers. The input is on one arm; and the output, taken from the other arm, depends on the phase difference between the arriving signals. The amplitude of the output varies sinusoidally with wavelength.

[0005] To make the MZI into a reconfigurable multichannel filter, a router is disposed in one of the arms to separate the channels among a plurality of channel arms. Each channel arm is provided with a phase shifter, and the channels are recombined at a second router. Control of the phase of each channel permits control of its amplitude.

[0006] A difficulty with this approach is that the MZI sinusoidal response acts as a narrow band filter. This has the drawback of narrowing the bandwidth of each channel. Accordingly there is a need for an improved multi-channel filter with enhanced channel bandwidth.

SUMMARY OF THE INVENTION

[0007] In accordance with the invention, an MZI-based reconfigurable multi-channel filter is provided with enhanced channel bandwidth by adding an all-pass filter to one or both of the MZI arms. The result is a square-shaped amplitude response closely approximating the ideal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The advantages, nature and various additional features of the invention will appear more fully upon consideration of the illustrative embodiments now to be described in detail. In the drawings:

Fig. 1 illustrates a conventional MZI-based reconfigurable multi-channel filter;

Fig. 2 illustrates an improved MZI-based reconfigurable multi-channel filter;

Fig. 3 is graphical illustration showing the improved response of the Fig. 2 filter; and

Fig. 4 is an alternative embodiment of the Fig. 2 filter.

[0009] It is to be understood that these drawings are for purposes of illustrating the concepts of the invention and are not to scale.

DETAILED DESCRIPTION

[0010] Referring to the drawings, Fig. 1 schematically illustrates a conventional MZI-based reconfigurable multi-channel filter comprising, in substance, an MZI 10 comprising a pair of waveguide arms 11, 12 extending between a pair of couplers 13, 14. The waveguide arms have approximately equal optical pathlengths L and L + ΔL, so if the input is applied via arm 11 at coupler 13, the output to arm 12 at coupler 14 depends on the precise phase difference between the arriving signals. Transmission will be a maximum at wavelengths for which the signals on the two arms constructively interfere. Specifically, if $\Delta\phi$ is the phase difference between the two arms, the spectral response of the device is a series of transmission maxima where $\Delta\phi$ is an odd multiple of π. For a multi-channel system, the communication channels are also periodic, and the MZI can be designed so that its periodic transmission maxima correspond with a plurality of channels.

[0011] In order to convert the MZI into a multi-channel filter, one of the arms is provided with a pair of waveguide grating routers (WGRs) 15, 16 and phase shifters 17A, ..., 17D are disposed in each of the waveguides connecting the routers. One router, e.g. 15, acts as a demultiplexer to separate the multichannel signal into a plurality of constituent channels and present each channel on a separate wavepath. The second router, e.g. 16, acts as a multiplexer to recombine the channels for passage to the output coupler 14. The phase shifters 17A, ..., 17D permit independent filtering of each of the channels wavepaths. Since the output level depends on constructive interference, it is highly de-

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pendent on the phase at which the channel arrives at the output coupler. Using the phase shifter to shift the phase of a channel away from constructive interference thus attenuates the channel. Further details concerning the structure and operation of this filter can be found in C. Doerr *et al.*, "Integrated WDM Dynamic Power Equalizer with Potentially Low Insertion Loss," IEEE Photon. Technol. Lett., Vol. 10, pp. 1443-1445 (1998) and C. Doerr *et al.*, "Dynamic Wavelength Equalizer in Silica Using the Single Filtered Arm Interferometer," IEEE Photon. Techn. Lett., Vol. 11, pp. 581-583 (1999), both of which are incorporated herein by reference.

[0012] Fig. 2 illustrates an improved MZI-based reconfigurable multi-channel filter similar to the filter of Fig. 1 except that an all-pass filter 20 is formed on at least one of the MZI arms, e.g. 11. This is accomplished by disposed a waveguiding ring resonator 21 sufficiently close to the arm to optically couple with the arm.

[0013] In operation, a light pulse traveling in the arm couples in part to the ring resonator 21. After transit around the ring, the light couples back to the arm. Interference between light from the resonator and light transmitted on the waveguide produces a frequency dependent time delay that compensates dispersion. The performance of the all-pass filter depends primarily on two parameters: 1) the ring radius, and 2) the coupling strength between the ring and the arm. The ring radius determines the free spectral range (FSR) of the all-pass filter. The response is periodic in frequency and can be matched to the spacing of a plurality of communication channels. The coupling strength determines the maximum group delay and the bandwidth of the delay. Further details concerning the structure and fabrication of all-pass filters are set forth in EP-A-0997 751.

[0014] Fig. 3 is a schematic graphical illustration showing the improvement in spectral response exhibited by the filter of Fig. 2. The solid lines (Curves 1) show the response of the Fig. 2 filter. The dashed lines (Curves 2) shows the response of a corresponding conventional Fig. 1 device). As can be seen, the improved Fig. 2 device has more nearly square responses than the Fig. 1 device.

[0015] Fig. 4 schematically illustrates an alternative embodiment of an improved filter in accordance with the invention using a folded MZI. The Fig. 4 embodiment is similar to the Fig. 2 embodiment except that the arms 11, 12 are folded by reflection. The routers 15, 16 are replaced by a slab multiplexer 41, and the ring resonator all-pass filter is replaced by an etalon all-pass filter 42. The upper arm 11 is coupled to the etalon all-pass filter and an optical signal is reflected back. Similarly, multichannel light in the lower arm 12 enters the slab multiplexer 41 which divides the signal into separate channels presented on separate waveguides 18A, ..., 18X. Each of waveguides 18A, ..., 18X includes a separate phase shifter 17A, ..., 17X, and each waveguide terminates in a mirror (not shown) reflecting the signal back through its respective waveguide to the multiplexer 41. The signals are recombined in the multiplexer and presented to arm 12 in the reverse direction. Further details concerning the structure and fabrication of a folded MZI are set forth in EP-A-0 940 698.

[0016] It is to be understood that the above-described embodiments are illustrative of only a few of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can be readily devised by those skilled in the art without departing from the scope of the invention.

Claims

1. In a reconfigurable multi-channel optical filter comprising a pair of optical waveguide arms forming a Mach-Zehnder interferometer, and optically coupled to at least one of the arms, an optical demultiplexer to separate a plurality of optical channels among a plurality of optical wavepaths, each wavepath including a phase shifter, and an optical multiplexer combining the channels for further transmission in the arm;

   THE IMPROVEMENT WHEREIN,

   an all-pass optical filter is optically coupled to at least one of the arms.

2. The optical filter of claim 1 wherein the demultiplexer comprises a waveguide grating router.

3. The optical filter of claim 1 wherein the multiplexer comprises a waveguide grating router.

4. The optical filter of claim 1 wherein the all-pass filter comprises an optical waveguide resonator ring.

5. The optical filter of claim 1 wherein the multiplexer comprises a slab multiplexer.

6. The optical filter of claim 1 wherein the all-pass filter comprises an etalon all-pass filter.

7. The optical filter of claim 1 wherein the optical waveguide arms are folded by reflection.

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FIG. 1

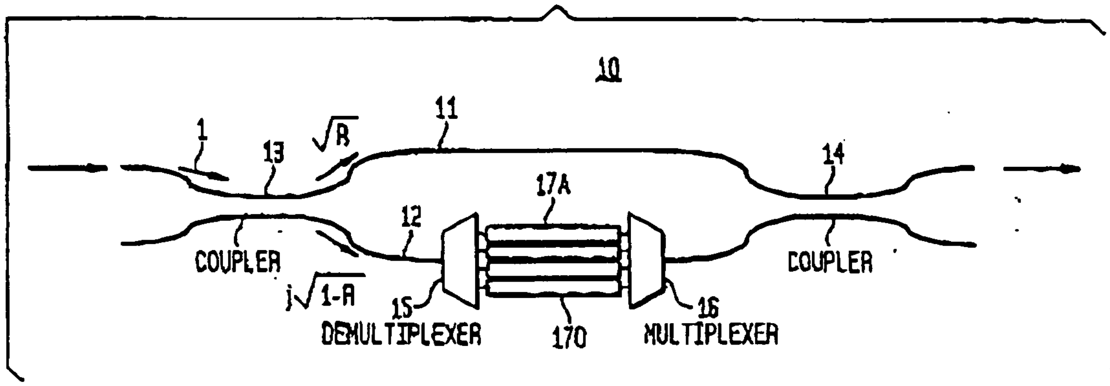

FIG. 2

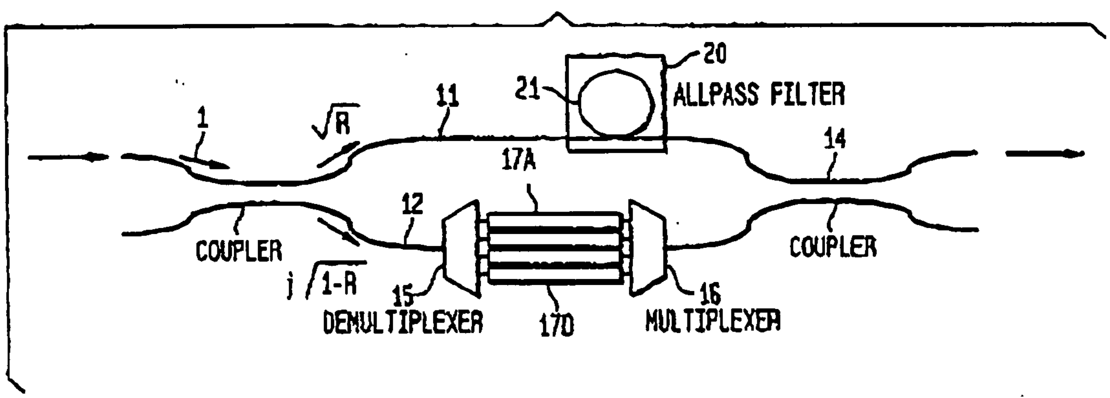

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FIG. 3

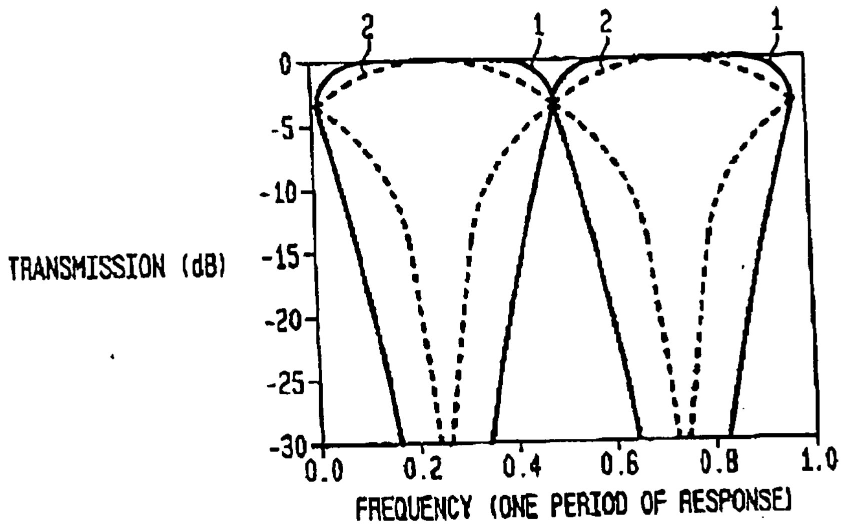
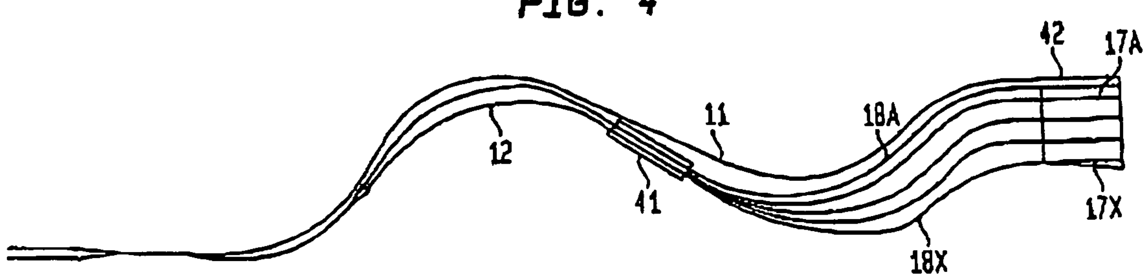


FIG. 4



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